Investigating the Breeding Capabilities of Hybrid Soliton Reactors

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ABSTRACT

Nuclear energy production asks for an optimized utilization of available natural resources and a safe operation of reactors. A closed fuel cycle requires the mass of fissile material depleted in a reactor to be equal to or less than the fissile mass produced in the same or in another reactor. In this work, a simple system of closed cycle is investigated, grounded on the use of a thermal, water-cooled subcritical Hybrid Soliton Reactor (HSR). The reactor is a specific Accelerator Driven System (ADS) and operates at lower power than usual PWR’s. This type of reactor is inherently safe, since shutdown is achieved by simply interrupting the accelerator’s power supply. First, a simple model is described which exhibits the properties which can be expected for HSR systems operating in a breeder configuration. Then, preliminary simulations are shown, which point at the existence of solutions allowing the design of realistic systems.
1 INTRODUCTION

Safety and proliferation resistance are at the origin of serious difficulties to be faced by nuclear industry. In this context, small encapsulated HSR’s with equal core and reactor lifetimes are of particular interest as they can provide efficient solutions to these problems.

Fission product management and closed fuel cycle also represent important challenges for nuclear energy. Breeding and closed fuel cycles are usually achieved in sodium-cooled reactors, as in conventional pressurized water reactors neutron capture and leak prevent breeding. Breeder reactors then have to face corrosion problems, difficulties with their inspection program, absence of first confinement barrier, polonium production, etc. Thermal breeder reactors based on HSR’s, using a different neutron economy, represent a promising approach for bypassing these problems, with further advantages:

- Neutron leakage can be reduced by peaking the neutron flux around the neutron source
- Large capture on fertile material can be accepted due to a lower multiplication factor
- Due to sub-criticality, systems that absorb neutrons at the beginning of cycle (BoC) are not necessary: borated water is not needed, control rods are used for safety only and remain withdrawn during reactor operation.
- Quasi constant shape and amplitude of power density distribution, neutron flux and fission product inventory can be achieved.

The HSR concept has been described and analyzed in previous work [2, 3, 4]. Its power distribution profile remains constant in time and thus limits the use of neutron absorbing rods to safety task only. The reactor is subcritical and has a lifetime of the order of three decades. Its core is encapsulated and therefore offers higher proliferation resistance. The fission products and actinides management is greatly simplified since no spent fuel storage pool is necessary. Furthermore, the reactor operation is quasi-continuous since no fuel reshuffling is performed.

The HSR core sub-criticality allows one to avoid the use of reactor poisons such as boron to compensate for excess reactivity at BoC. Furthermore, the neutron flux and power distribution are peaked around the neutron source, implying considerably reduced neutron losses in comparison with critical reactors. These features contribute to a better neutron economy, triggering the investigation of the HSR use in a breeder regime in order to achieve a closed fuel cycle.

In this work, a simple model and simulations are presented that allow one to identify the conditions under which breeding is possible, preserving at the same time the reactor stability and the system efficiency. Preliminary results for a conceptual HSR breeder are presented.

2 SIMPLE MODEL

The reactor is schematically modelled as an infinitely long tube of fertile and fissile materials, with a neutron source moving along its symmetry axis. The reactor behaviour is obtained using the two-group approximation for neutrons, representing slow (thermal) neutrons and fast neutrons [1]. This approximation appears to be sufficient to determine conditions under which a HSR can be breeder and energetically profitable.

At any abscissa z of the axis of the tube, and at any time t, the state of the reactor is given by a simple set of variables, namely:
(i) $n_T$ and $n_F$ which describe the linear densities, that is the number per unit length, of thermal and fast neutrons respectively ($n = n_T + n_F$ is the total linear neutron density)

(ii) $(q_1, q_2, q_3)$ which describe the isotopic composition of the reactor core: $q_1$ is the linear density of fertile material, for example $^{238}U$, which can absorb neutrons and transmute to fissile material; $q_2$ is the linear density of fissile material, for example $^{239}Pu$ which is produced from fertile material by absorption of neutrons and can produce fissions when it absorbs neutrons; $q_3$ is the linear density of fission products, which can be destroyed by absorption of neutrons.

The heat produced in the core is assumed to be properly evacuated. For our discussion, the evolution equations for fissile material and total neutron densities are sufficient:

$$
\frac{\partial q_2}{\partial t} = -(\alpha_2^T n_T + \alpha_2^F n_F)q_2 + (\alpha_1^T n_T + \alpha_1^F n_F)q_1
$$

$$
\frac{\partial n}{\partial t} = -(\alpha_1^T n_T + \alpha_1^F n_F)q_1 + \mu(\alpha_2^T n_T + \alpha_2^F n_F)q_2 + \Delta n - \beta n + S
$$

($\alpha_1^T, \alpha_2^T$) and ($\alpha_1^F, \alpha_2^F$) describe the probabilities to be absorbed by a fertile or a fissile nucleus (proportional to the corresponding cross sections) for a thermal and a fast neutron respectively; $\mu$ is the number of excess neutrons produced by each fission; $\Delta$ is a diffusion operator; $\beta$ describes the total probability for neutron losses, including parasitic absorptions by structural materials, escaping from the core and absorption by fission products; $S$ is the neutron source.

Known values for the cross sections of neutrons on existing fertile and fissile materials justify to complete the two-group model with the following relative orders of magnitude for the coefficients ($\alpha_1^T, \alpha_2^T$) and ($\alpha_1^F, \alpha_2^F$) (see, for instance, [1])

$$\alpha_1^T \ll \alpha_2^T \sim \alpha_2^F \sim \alpha_1^F \sim \alpha$$

Absorptions can be neglected in front of fissions for thermal neutrons, while both have probabilities of similar magnitude for fast neutrons. The variation of fissile material is mainly governed by the amount of fission processes overbalance losses [2], with a multiplication factor taking a simple form

$$
k_{eff} = \frac{\mu \alpha q_2}{\alpha \nu q_1 + \beta}, \quad \nu = \frac{n_F}{n}
$$

$k_{eff}$ decreases with the proportion of fast neutrons $\nu$, and mainly with the amount of fission products (as the latter increases $\beta$, hence neutron losses).

Equations [124] determine the qualitative behavior of the reactor. When the source $S$ is activated, fast neutrons are locally generated. As shown by equation [2], these fast neutrons rapidly diffuse and thermalize. Hence, a non vanishing density of thermal neutrons appears at any position in the core before it has been reached by the moving source. So that neutron densities evolve from an initially non vanishing density $n = n_T$ of thermal neutrons.

Equation [1], with $n_F = 0, n = n_T \neq 0$, implies that the density of fissile material at a given location in the core decreases at early times, its time derivative being negative ($\frac{\partial q_2}{\partial t} \sim \alpha(n_F q_1 - n q_2) < 0$). As soon as the source reaches this location, an increasing number of fast neutrons is created ($n_F \neq 0$). The resulting transmutations of fertile material into fissile material, due to the much larger density of fertile material, overbalance the fissions induced by thermal neutrons, leading to an increase of fissile material ($\frac{\partial q_2}{\partial t} > 0$). Adjusting the source intensity with respect to initial fertile and fissile densities, one may reach a final state where the initial fissile density is recovered and the reactor follows a closed fuel cycle.

A strong constraint is to maintain a positive global energy output. Considering the high efficiencies which can be achieved (2/3 of electricity converted into beam power by accelerator
and 1/3 of heat converted into electricity), an energy multiplication factor (emf) of 10 for the reactor means that 60% of the electricity produced goes to the network while 40% goes to the accelerator. In the HSR configuration, such an emf can be achieved with subcritical cores ($k_{eff} \sim .9$) provided that during operation $k_{eff}$ does not depart too much from its initial value.

Initial densities and source intensity can be chosen so that to limit the variations of fissile and fertile materials during a cycle. Simultaneously, the proportion $\nu$ of fast neutrons also remains small. Equation (4) shows that $k_{eff}$ follows a regular decrease, mainly due to the accumulation of fission products which increases the neutron losses $\beta$. Limiting the amount of fission products then allows one to achieve a global energy output while ensuring safety.

3 SIMULATIONS

Simulations have been performed to test the breeding capacity of a thermal reactor based on a HSR and obtain feasibility conditions that can be realized with presently achievable systems. For that purpose, the Monte Carlo code ANET (Advanced stochastic Neutronics Evolution and Thermal code), described in a previous work [4, 5], has been used.

3.1 Design of the HSR breeder

The simulated HSR thermal reactor is a subcritical ADS, described in Figure 1.

Figure 1: Design of the HSR breeder. The central tube of the vessel $\Phi$ is empty, forming a channel through which a source of neutrons moves at a velocity which can be modulated. The neutron source $\sigma$ is a beam of protons $\beta$ from an accelerator, which hit the internal tube $\tau$ (called “window”, made, for instance, of tungsten) and then produce neutrons. Driven by electromagnets $\epsilon$, the neutron source $\sigma$ is moving with a constant speed along the axis of the cylinder.

The core contained in the vessel includes tubes of fuel surrounded by the water of the primary cooling system which is also a moderator. The reactor is conceived to operate for several
decades (e.g. 30 years) without refuelling or reshuffling, with constant characteristics. The core is divided along its axis into 500 coaxial cylindrical slides, allowing for a sufficiently precise assessment of material distribution. 20 m long $^{238}\text{U}/^{239}\text{Pu}$ fuel pins of 2 cm diameter have been considered; the fuel enrichment in $^{239}\text{Pu}$ is a tuning parameter, chosen to be a few percent.

Accelerators with 1 GeV proton energy, some mA of intensity and 66% efficiency are anticipated. Usual efficiency of thermal reactors is around 33%. The dimensions of the system (length, radius), the characteristics of the fuel (enrichment, pin constitution), of the beam (energy, intensity, spreading) and of the target-window (geometry, constitution, dimension) can be tuned to optimize the system. A 22 cm thick (22 cm appears as an optimum for reflecting neutrons) and 20 meter long cylindrical stainless steel vessel of 68 cm of internal radius is considered. As a hadronic shower has a dispersion length of about one meter in heavy material like iron, a core length of 20 meters seems necessary.

Cylindrical spallation targets with various thicknesses have been tested. The thickness must be sufficient to generate neutrons but not too important, to resist to pressure and to ensure the evacuation of heat produced during spallation. With a melting temperature of 3400 °C, tungsten appears as a good choice for the window. An internal radius of 5 cm has been chosen, as a 1 Gev proton interaction spreads over several dm.

### 3.2 Implementation in ANET

The ANET code [4, 5] simulates the protons interacting with the window material, therefore the neutron source, the neutrons interacting with core materials and the other low and high energy particles (gammas, pions, electrons) in the reactor. It allows one to simulate the core inventory evolution, the spallation target composition and to take into account temperature effects. Fission products are collectively represented by a single pseudo-fission product. The code output provides information on neutron fluxes, energy and fission distributions, fission products, fissile and fertile material distributions and evolution with time.

Simulating the system with good statistics (100 000 protons, representing each 0.1 day of operation), needs about 36 hours on a usual single processor. 10 000 protons, each representing 1 day, are sufficient to estimate the system behaviour, taking into account statistical errors.

### 3.3 Preliminary results

The behaviour of the fissile material within the core, of the multiplication factor and of the energy output are summarized in Table 1, showing the averaged performance of the reactor over 10 000 days (about 30 years). In Figure 2 the corresponding values are plotted against the value of the beam power or the amount of fission products.

**Breeding capacity**

After a decrease, the amount of fissile material follows a regular increase, clearly showing the breeding capacity. Moreover, the variation of the total amount of fissile material remains limited to a few parts per thousand over a large evolution range (a few kgs for an initial amount of 2 tons). A closed fuel cycle is obtained for a reasonable beam power ($\sim 3\text{MW}$).

**Energetic efficiency**

As expected, breeding is obtained at the price of a loss in energetic efficiency. Table 1 and Figure 2 clearly show a regular decrease of the multiplication factor $k_{eff}$ which persists once breeding is established. However, the variations of $k_{eff}$ remain limited and the energy output is
satisfactorily sustained. The total energy output is moreover increased by a larger beam power. The energetic efficiency is ultimately limited by the amount of fission products.

**Reactor stability**

The multiplication factor $k_{\text{eff}}$ decreases with the amount of accumulated fission products, thus driving the core material to a stable state after the passage of the source. This allows the reactor to maintain a regular behaviour over large timescales of evolution. This regular behaviour is preserved when increasing the beam intensity. These features are in contrast with those of fast HSRs [2]. For a breeding thermal HSR, criticality problems may occur at BoC only, where they can be managed with usual techniques.

The reactor stability is illustrated in Figure 3 showing the variations of the distribution of fission products in the core, in time and along the axis of the beam. Fluctuations are mainly due to statistical errors.

![Figure 3: Evolution of the reactor performance.](image)

**Table 1: Evolution of the reactor performance.**

<table>
<thead>
<tr>
<th>beam mA</th>
<th>beam power MW</th>
<th>keff</th>
<th>energy ampl factor</th>
<th>therm power MW</th>
<th>fission product kg</th>
<th>elect in network MW</th>
<th>budget Pu9 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0001</td>
<td>0.984</td>
<td>96.8</td>
<td>0.00326</td>
<td>0.523</td>
<td>0.0031</td>
<td>-0.024 kg</td>
</tr>
<tr>
<td>0.1</td>
<td>0.15</td>
<td>0.978</td>
<td>61</td>
<td>6.1</td>
<td>44.215</td>
<td>1.83</td>
<td>-1.613</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3</td>
<td>0.97</td>
<td>48.6</td>
<td>9.72</td>
<td>75.704</td>
<td>3.94</td>
<td>-2.296</td>
</tr>
<tr>
<td>0.5</td>
<td>0.75</td>
<td>0.956</td>
<td>32.8</td>
<td>16.4</td>
<td>139.703</td>
<td>4.66</td>
<td>-3.117</td>
</tr>
<tr>
<td>1.</td>
<td>1.5</td>
<td>0.941</td>
<td>24.4</td>
<td>24.4</td>
<td>212.246</td>
<td>6.66</td>
<td>-3.167</td>
</tr>
<tr>
<td>2.</td>
<td>3</td>
<td>0.919</td>
<td>18</td>
<td>36</td>
<td>309.120</td>
<td>9</td>
<td>-0.433</td>
</tr>
<tr>
<td>3.</td>
<td>4.5</td>
<td>0.903</td>
<td>15</td>
<td>45</td>
<td>377.655</td>
<td>10.5</td>
<td>+1.917</td>
</tr>
<tr>
<td>4.</td>
<td>6</td>
<td>0.89</td>
<td>13.7</td>
<td>54.8</td>
<td>432.512</td>
<td>12.3</td>
<td>+3.839</td>
</tr>
<tr>
<td>5.</td>
<td>7.5</td>
<td>0.872</td>
<td>11.5</td>
<td>57.5</td>
<td>476.919</td>
<td>12.5</td>
<td>+8.558</td>
</tr>
</tbody>
</table>

**Figure 2: Evolution of the reactor performance.**

4 DISCUSSION

Several parameters can be tuned to optimize the reactor performance. We discuss the constraints they should satisfy.

- Accelerator energy, beam nature and spreading

Increasing the beam energy increases the neutrons production efficiency, but requires a greater accelerator. Other nuclei (deuterons, alphas) rather than protons can also be used to increase this efficiency. The beam spreading on the window must be sufficient to avoid local melting. But this spreading must not be too large in order to keep the candle character of the HSR.

- Spallation target (window) geometry and material composition

The target material must be sufficiently heavy to have a good spallation efficiency. It must be resistant and show both a high thermal conductivity (for efficient heat removal) and a high melting point. Therefore, various materials such as tungsten or iron must be examined. The internal radius of the cylindrical spallation target is also a parameter to be tuned, as the heat produced by spallation must be properly evacuated and enough room must be reserved to drive the beam. The optimum thickness of the window is obtained from a compromise between neutron production and the efficiency of heat removal.

- Dimension, length and radius of the reactor

The candle character of the reactor imposes a long vessel. A factor of more than 10 between the core length and the hadronic shower spreading on the target is necessary in order to have a constant behaviour in a large fraction of the operational life of the reactor. This problem must be specifically studied. For a given enrichment, the radius is
determined by the power distribution, which in case of a subcritical reactor has a radially exponential shape. Peripheral fuel pins act as blankets, having small contribution to the global power. In this first study, as a good compromise, a 68 cm radius and a 20 m core length have been chosen.

- **Enrichment**
  
  A higher enrichment implies a higher reactivity. It also requires a smaller reactor core. Enrichment can be kept low with a core of reasonable size. In this first study, a uniform enrichment has been considered throughout the reactor core. This can certainly be improved. Enrichment remains low (3%), but the total fuel load is important. This allows for a continuous operation without external intervention during the reactor’s lifetime.

## 5 CONCLUSION

ANET simulations show that a thermal breeder HSR can be conceived to reach a minimum of performances. It appears possible to realize a closed fuel cycle based on a thermal HSR, operating at low and medium power. A breeding capacity can be obtained while preserving the energetic efficiency and the stability of the reactor. Low enrichment ratios are favored, while fission products management is only required at the end of cycle, which coincides with the end of the reactor’s life. The accelerator power (10-20 MW maximum) and the energy multiplication factor (60 maximum) seem to limit to the maximum power that can be obtained with such a system.

Subsequent studies will aim at optimizing the parameters examined in this preliminary work, following interrelated constraints due to energetic objectives, heat evacuation, safety and waste management (waste is kept inside the reactor vessel until final dismantling). To this end, the various components of the ANET simulation tool (accelerated proton, spallation target and core inventory evolution) will be further improved and qualified. The code is also foreseen to be developed towards receiving thermal hydraulic feedback.

## REFERENCES


